AN EXPERIMENT ON ELECTRON BEAM TRANSPORT IN AN ARRAY OF WIRES*

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Abstract

We have investigated experimentally the propagation of a relativistic electron beam through an array of parallel conducting wires. Theory and particle simulation predict such an array will provide both charge and current neutralization, allowing beam transport above the drift tube limit. We injected a 60 ns, 17 kA (120 A/cm^2) pulse of 1.4 MeV electrons into an array of 1 m long wires spaced 1 cm apart, filling a hexagon 15 cm across. Arrays have been tested with 12 mil diameter copper wire, 3 mil stainless steel wire, and 12 mil copper wires terminating on an insulated, segmented beam dump. $\dot{\mathbf{B}}$ probes and streak camera data show that 67% of the current is transported in the case of the stainless steel array. The copper wire array transported electrons for 20 ns only. The beam is injected with a 250 mrad divergence, and the transported beam has a divergence of less than 100 mrad. Follow-up experiments are to use thinner wires to improve both the propagation and divergence of the beam.

Introduction

This paper presents the results from an experiment in electron beam transport using a wire array to neutralize the charge and current of the beam [1]. Traditional methods of improving beam transport include using an external magnetic field and propagating the beam in a background plasma. The beam is injected into an array of wires oriented parallel to the direction of propagation of the beam. The grounded wires charge neutralizes the beam, and the return current in the wires partially cancels the beam current. The beam must have a finite transverse energy to prevent collapse of the beam on the wires due to the potential wells between wires. For this experiment the minimum transverse energy is calculated to be 800 eV.

†on leave of absence at Office of Naval Research, London, U.K.

*Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

Experimental Apparatus and Diagnostics

The experimental apparatus is sketched in Fig. 1. The electron beam is created by field emission from a velvet covered cathode charged to −1.4 MV. A Marx bank and pulse forming line [2] is used to make a 60 ns pulse, which produces the characteristic output current shown in Figs. 7-9. The anode of the diode is a stainless steel plate 6 cm from the cathode. This plate has an array of 253 holes of diameter 0.92 cm spaced on 1 cm centers. Behind the anode plate (0.5 cm) is the aluminum front plate of the wire array, which has the same hole pattern as the anode. At the interstices of the holes are attached the wires, which extend 1 m perpendicular to the plate and terminate on a plate similar to the front plate. A regular array of 282 wires is formed, which has a mean radius of 8.4 cm. The array is enclosed in a vacuum chamber of 12.7 cm radius. The range of background pressure was between 10^{-5} and 10^{-4} torr.

Arrays were also constructed with a segmented beam dump, in which the wires terminate on brass buttons attached to acrylic rods of varying heights, Fig. 2. This insulates the wires from ground and other wires, forcing the electron current reaching a beam dump segment to return along the local wire. The neutralizing return current then has the shape of the beam profile so that the cancellation forces are better balanced radially. In addition, the radial electric field is not shorted at the end of the array, which prevents beam pinching in the dump region. A small fraction (0.093) of the beam passes through the spaces between the dumps. This fraction is collected by a copper rear plate with holes to form beamlets for the streak camera. The return path for this current is the vacuum chamber walls. The wall current ensures that the wire current is less than the electron beam current and provides a radial confining force.

Smaller arrays of 30 wires (2.8 cm mean radius) were also tested. These arrays were made with a 19 hole front plate.

The beam passes through the end plate of the array and terminates on a tantalum beam dump. The current has a

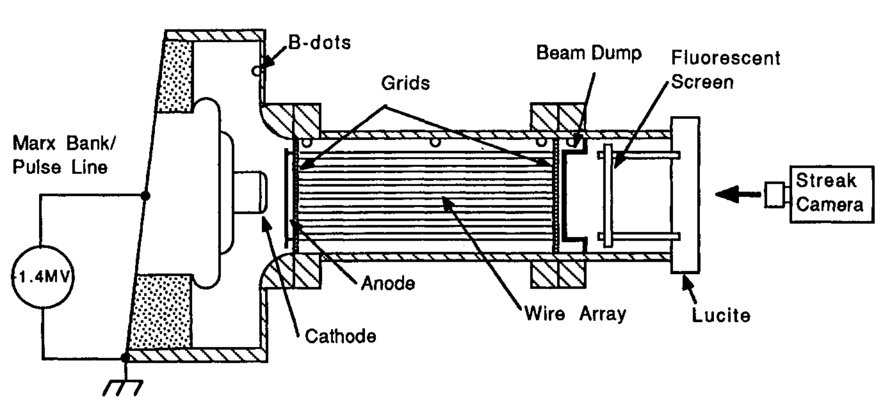

Fig. 1. Experimental layout.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1989	**N/A**	**-**

4. TITLE AND SUBTITLE
An Experiment On Electron Beam Transport In An Array Of Wires

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lawrence Livermore National Laboratory P.O. Box 808, Livermore CA 94550

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
We have investigated experimentally the propagation of a relativistic electron beam through an array of parallel conducting wires. Theory and particle simulation predict such an array will provide both charge and current neutralization, allowing beam transport above the drift tube limit. We injected a 60ns, 17kA (120A/cm2) pulse of 1.4MeV electrons into an array of 1m long wires spaced 1 em apart, filling a hexagon 15 em across. Arrays have been tested with 12 mil diameter copper wire, 3 mil stainless steel wire, and 12 mil copl!er wires terminating on an insulated, segmented beam dump. B probes and streak camera data show that 67% of the current is transported in the case of the stainless steel array. The copper wire array transported electrons for 20 ns only. The beam is injected with a 250 mrad divergence, and the transported beam has a divergence of less than 100 mrad. Follow-up experiments are to use thinner wires to improve both the propagation and divergence of the beam.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

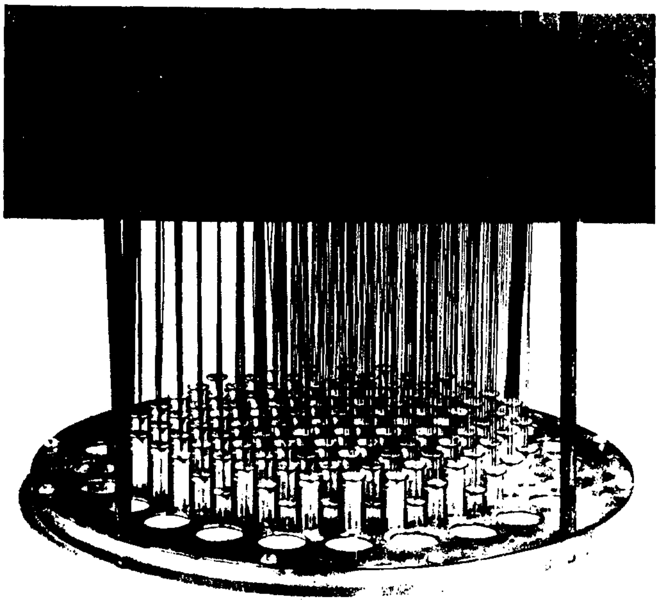

Fig. 2. Segmented beam dump with wires attached.

preferred return path through the low impedance wire array (rather than the vacuum chamber walls). The tantalum plate has a row of 1 mm holes spaced 1 cm apart along the horizontal center chord of the beam, which sample the beam by creating beamlets. The beamlets passing through these holes then drift for a fixed distance (usually 5 cm) and strike a plastic (acrylic) screen, which fluoresces when bombarded by electrons. The screen is imaged through the acrylic back end of the vacuum chamber to a streak camera. The image is then analyzed to find beam divergence and profile.

The energy of the exiting electron beam is found by blocking the streak beamlets with various thickness of copper strips and measuring the resulting attenuation of streak image intensity. This is compared to an empirical equation [3], which tells us the expected attenuation of electrons of a given energy through copper.

The current at 5 axial and 4 azimuthal locations is measured using numerically integrated $\dot{\mathbf{B}}$ probes and self-integrating (current viewing resistor) **B** probes. Beam loss to the walls is checked with Faraday cups oriented facing the wires.

Experimental Results

Fig. 3 is an example of the digitized output from the camera. This streak image was taken without a wire array, using the beam dump as the anode and was used to characterize the input electron beam. A line-out of this data (at $t = 20\,\mathrm{ns}$ into the streak) with least squares fit is shown in Fig. 4. The data is fitted to shifted guassians on a parabolic background. From the fitted function the intensity, width and position of each streak is obtained. The position of each streak gives the transverse distance moved by the electrons as they travel between the beam dump and the fluorescent screen, which is used to calculate beam divergence. The divergence as a function of radius and time for the diode is shown in Fig. 5. The intensity of each streak is used to get the profile of the beam, Fig. 6, and the width of a beamlet is used to calculate the transverse temperature. For the diode, the beam temperature was calculated to be $< 1.4\,\mathrm{keV}$.

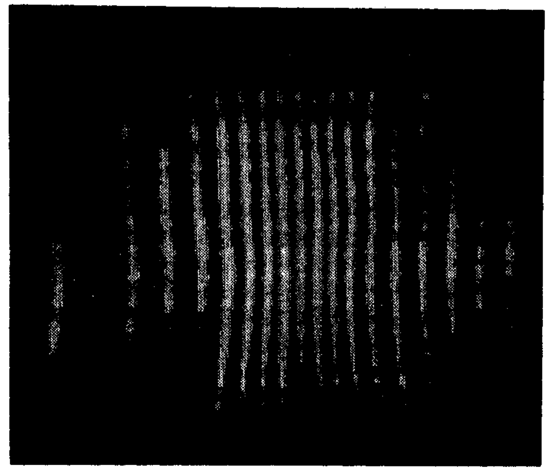

Fig. 3. Streak camera image for diode.

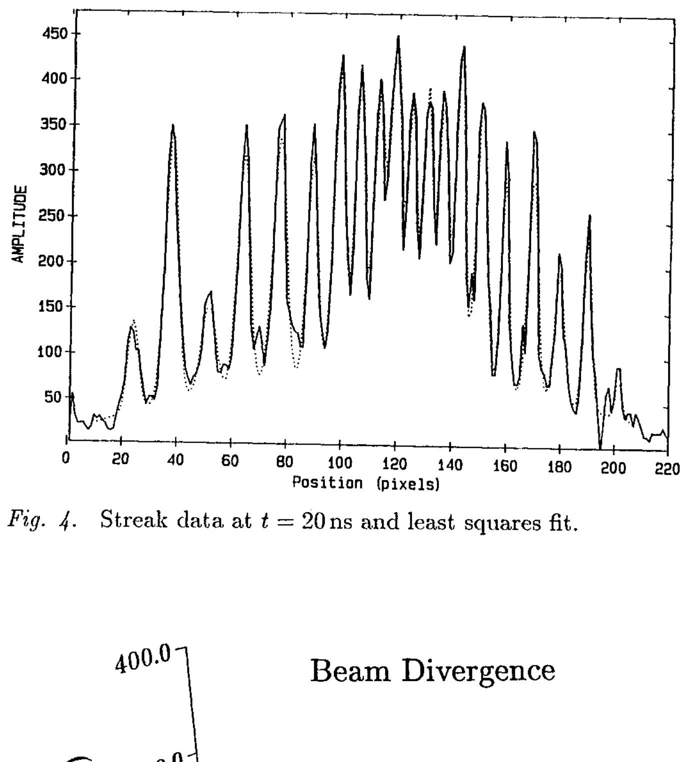

Fig. 4. Streak data at $t = 20\,\mathrm{ns}$ and least squares fit.

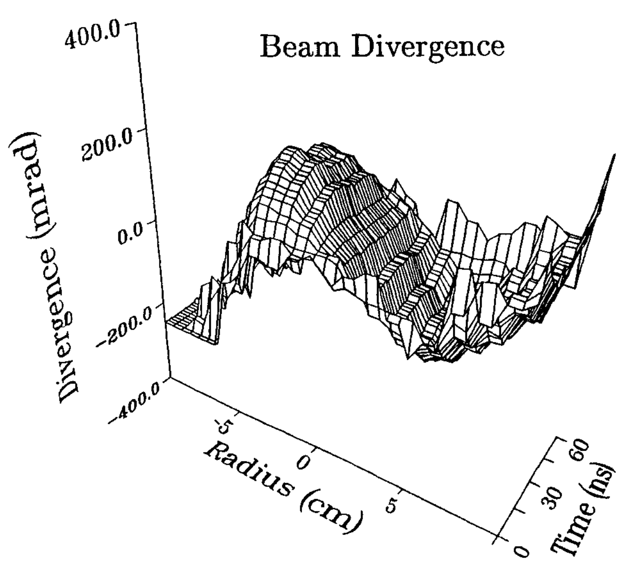

Fig. 5. Beam divergence from streak camera data.

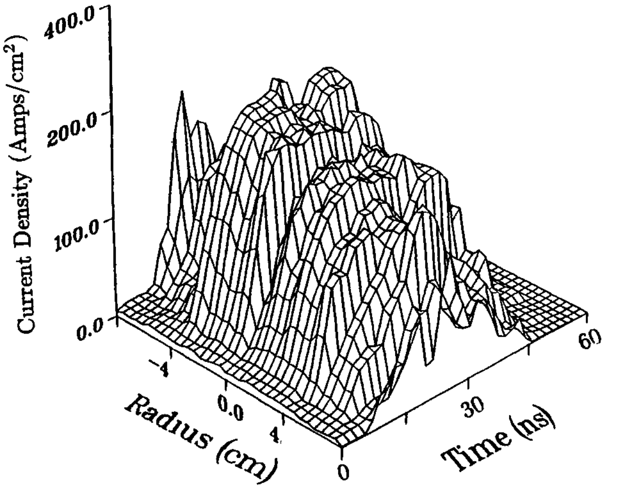

Fig. 6. Beam profile from streak camera data.

The currents of interest are calculated from the raw data as follows. The $\dot{\mathbf{B}}$ signals are integrated, and the $\mathbf{B}$ signals are corrected for the integration time constant of the probes. The input current (electron current injected into the array) is calculated by multiplying the field emitted electron current by a factor of 0.78 to account for the scrape-off by the front grid. This factor was measured without wires and is close to the calculated geometric transmission of the grid (0.82). The return wire current is calculated by subtracting this input current from the current measured by the $\dot{\mathbf{B}}$s located just behind the front grid, where the beam current enters the wire array. The output current (electron current exiting the array) is calculated in two ways. The first method uses the current into the beam dump corrected for backscatter from the tantalum (0.30) and the transmission of the final grid (0.82). The second method uses the current from a $\dot{\mathbf{B}}$ measurement made just before the beam exits the array. The wire current is subtracted from this current to give the output current. These two methods of output current calculation agree quite well (Figs. 7 & 8).

With the segmented beam dump, the beam dump current cannot be measured since the wires attach to the dump. The output current must be calculated using $\dot{\mathbf{B}}$ measurements made before the beam dump, subtracting the wire current, and factoring out the backscatter of the brass beam dumps (0.24). We also placed a Faraday cup to intercept the three center streak beamlets. This measurement can also be used to calculate the output current if the beam profile is known. The output current can also be found using an intensity calibration of the streak images. The calibration of the streak camera is done using the diode streak image and $\dot{\mathbf{B}}$ probe measurments.

The loss current, which represents the current hitting the stainless steel vacuum chamber wall, is found by simply subtracting the output from the input current. The loss current returns through either the wires or in the wall. The loss current at the wall is found using the Faraday cups. Assuming that the loss current density measured by the Faraday cups is evenly distributed along the last 70% of the wall gives reasonable agreement between the two measurements.

Without wires, an output current of 2 kA was measured for the nominal 17 kA input. This value is much higher than the value obtained in particle simulations, 0.1 kA. The discrepancy may be due to backscatter of the electrons from the vacuum wall. The energy of the exit electrons is estimated (using the copper strip attenuators) to be ≈ 600 keV. This supports the backscatter theory, since backscattered electrons would have less energy. All the tested arrays had an exit electron energy of about 1.4 MeV, which is the input energy. We plan to further investigate the no-wire array output current in the upcoming follow-on experiments.

The copper wire array gave disappointing results. For a 60 ns input pulse, the output current had about 20 ns duration and 10 kA amplitude, Fig. 7. Note that the output current begins to decay after following the initial 10 ns risetime of the input pulse.

We suspect that this premature cut-off is due to scattering of the electrons when they strike the wires. The wire diameter for this array was 12 mil, which makes the probability of an electron striking a wire 69% during one transverse transit across the array. The beam for this diode had an input divergence of up to 250 mrad, so the electrons can have a large initial transverse velocity.

With the stainless steel array this defect was alleviated by using thinner wires (3 mil diameter), which gave a

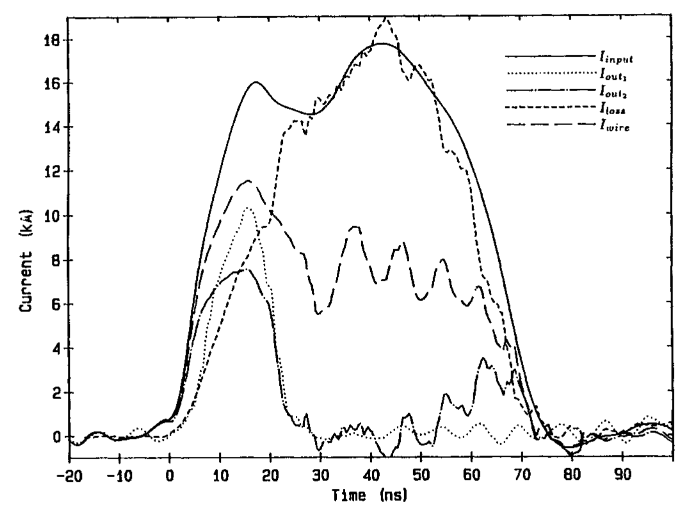

Fig. 7. Currents for 12 mil copper wire array.

17% probability of an electron hitting a wire during one transverse transit of the array. In addition, the stainless steel wires are much more resistive than copper (168 ohm/wire). This has the effect of decreasing the magnetic decay time, so that the flux is not trapped in the array. Therefore, the magnetic field is allowed to decay to follow variations in beam current. The experimental results show that the output pulse now follows the input pulse for the full 60 ns, with an amplitude of 10 kA, Fig. 8. However, the beam now has a larger transverse temperature of ≈ 50 keV and the beam is pinched to a 1.5 cm radius in the center of the array.

The segmented beam dump was conceived to correct this situation by tailoring the wire current to more closely approximate the beam current profile. Unfortunately, the large (280 wire) array of this type arced over and gave results very similar to the standard copper array. However, a small (30 wire) array did not break down, and gave an output current of 1.75 kA for an input current of 2.4 kA for the entire pulse duration of 60 ns, Fig. 8. The output current of this array as a percentage of the input current exceeds both the plain copper and steel arrays.

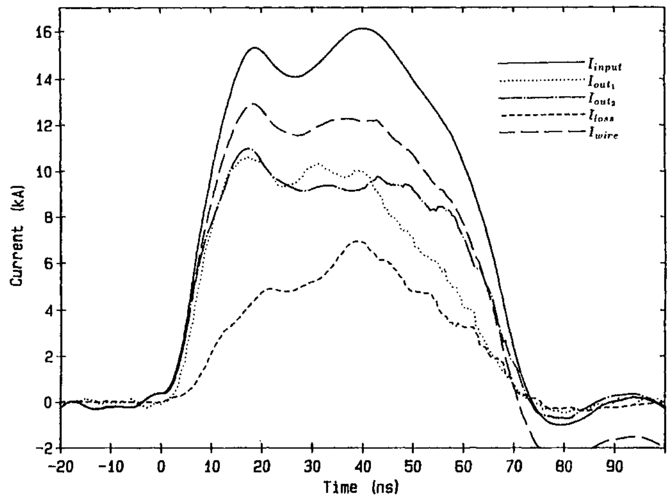

Fig. 8. Currents for 3 mil stainless steel array.

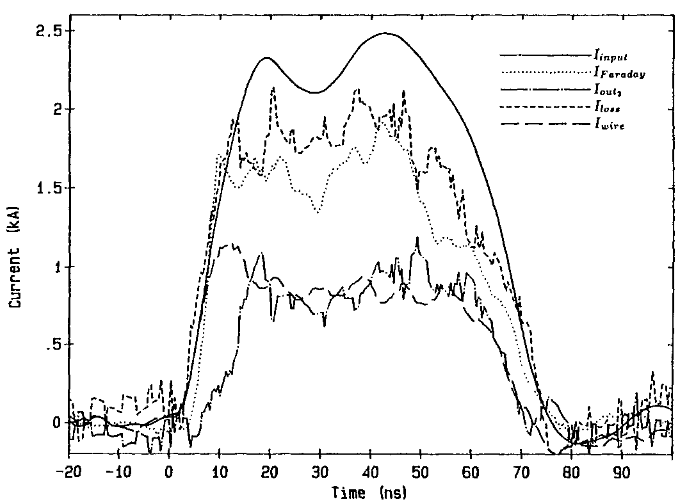

Fig. 9. Currents for small, segmented beam dump array

Selected Array Performance

Type of Array	Steel	Cu	T.S.	None
Wire current	.81	.73(.50*)	.24	-
Output current	.67	.67(.00*)	.73	.13
Wall loss	.32	.47(.95*)	.27	.86
Beam width (cm)	4	8	6	16
Profile (Flat or Gaussian)	G	G	G	F
Divergence (degrees)	5	14	2	2
Electron energy (MeV)	1.2	1.4	1.4	0.6

Current is fraction of injected current (through screen)
*current after 20ns

Conclusion

We have investigated experimentally the propagation of a relativistic electron beam through arrays of parallel conducting wires. Electron beam propagation in an array of 3 mil steel wires is observed to be enhanced compared to the vacuum case. An array of 12 mil copper wires showed enhanced transport only during the risetime of the injected pulse, followed by cutoff of current. We believe that the scattering of the electrons when they strike the wires causes this cutoff. The segmented beam dump (also made of 12 mil copper wires) shows the most enhancement in electron transport, however the injected current was smaller than the other arrays. Follow-on experiments are planned to investigate the effects of wire diameter and resistivity, and will include a full sized segmented beam dump array redesigned to stand off higher voltages.

Acknowledgements

The help of R. L. Druce with setup and operation of the streak camera was appreciated. Also the crew of the 2 MeV accelerator was greatly appreciated.

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